STREAMLINING SAFETY TESTING FOR MUNITIONS

by Marc DéFourneaux
NIMIC Project Manager

Abstract

Safety testing is generally done on very small numbers of munitions for reasons of cost. Therefore, obtaining high levels of confidence as the result of testing requires to design highly informative and reliable tests and to organize them into rational and cost-effective test programs.

Any individual test must obviously be representative of the threat or hazard it simulates, but it must also meet other conditions: be reproducible/reliable, be meaningful and informative (i.e. allow a good understanding of the test outcome) and be transferable (i.e. allow the extension of the results to other configurations than strictly that of the test). These requirements are not fully compatible, hence the need for compromises which may not always coincide with the current approach to standardized tests, because this approach places emphasis on representativity by trying to stick as closely as possible to the real scenarios. In particular, transferring results from a given test to other configurations can only be done by coupling experimental testing with mathematical modeling. This is true for "single" events such as fuel fire or single bullet impact, and still more for "compound" events such as multiple impacts.

Test programs can be of various types: "single label" or "multiple label" when their purpose is the attribution of a general qualification (e.g. "Insensitive Munition"), or "tailored" to the specific needs of a particular munition or family of munitions. Tailoring test programs requires a precise analysis of all the occurrences (both environmental and combat-generated) likely to be faced over a whole life cycle, but it enables specific threats or hazards to be considered (or eliminated if irrelevant), thus providing higher levels of confidence for lower costs.

Introduction

The aim of any type of statistical testing is to qualify a production as a whole from the analysis of a reduced sampling, with the highest possible level of confidence in the conclusions drawn from test results. In such industrial productions as machined parts, the definition of relevant dimensional and mechanical tests is easy, and the definition of the representative sampling to be tested and of the tolerances to be applied is a science per se ("chi squared" testing) which allows the calculation of confidence levels for the whole production. As far as safety is concerned, the munitions industry is far from being able to derive such confidence levels as the result of testing, for two main reasons:

		Form Approved OMB No. 0704-0188

Report Documentation Page

Form Approved
OMB No. 0704-0188

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE **AUG 1994**	2. REPORT TYPE	3. DATES COVERED **00-00-1994 to 00-00-1994**
4. TITLE AND SUBTITLE **Streamlining Safety Testing for Munitions**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **NATO/NIMIC,B1110 Brussels, Belgium,**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES **See also ADM000767. Proceedings of the Twenty-Sixth DoD Explosives Safety Seminar Held in Miami, FL on 16-18 August 1994.**		
14. ABSTRACT **see report**		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT **Same as Report (SAR)**	18. NUMBER OF PAGES **16**	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**			

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

- the number of possible variations of the real scenarios with respect to the nominal configuration of a given test is virtually infinite, so the usual probability calculations can not be applied;

- even if these calculations were possible, reaching high levels of confidence would normally require samplings with very large sizes, which is never the case because safety testing is generally destructive, hence expensive.

This makes it all the more necessary to design highly informative tests and to organize them into rational test programs.

1   Criteria for the design of safety tests

l. l   General approach

The first step of any test definition is the identification of all possible threats/hazards which may occur during the whole life of a munition. These may involve

- either single events (e.g. single fragment or bullet impact, e.g. fuel fire);

- or compound events (e.g. sequential events such as multiple fragment or bullet impact).

As long as mathematical models did not exist, the only way of assessing the behavior of a given munition to one of these threats/hazards was to simulate it experimentally by a test. This is certainly a good approach provided the test is carefully selected so as to be:

(a)   REPRESENTATIVE of the corresponding threat (e.g., when simulating fragment impact,
select a chunky cylinder rather than a long rod as the impacting projectile);

(b)   INFORMATIVE and MEANINGFUL, i.e. permitting the understanding of the test outcome (e.g., if a detonation occurs in a warhead, understand where and why a reaction
started and how it built up into a detonation);

©   REPRODUCIBLE per se, hence RELIABLE (e.g. avoid modes of projectile penetration
which result in random variations from one execution to another of the same test);

(d)   TRANSFERABLE, i.e. permitting an extension of the test outcome to other configurations than strictly that of the test.

1.2   Conflicts between different criteria

So far, the general tendency has been to place emphasis essentially on the first criterion above - representativity - by trying to stick as closely as possible to the real scenarios (e.g. simulating bullet impact with the impact of a real bullet on a real munition); but this is sometimes done at the expense of the other three requirements above:

> - at the expense of (b) because most tests on real munitions are done empirically without
> sufficient instrumentation to detect and follow with due precision how events occur;

> - at the expense of © because, in tests such as bullet impact, the penetration of the bullet often results in random instabilities which may totally alter the result of the test;

> - at the expense of (d) because the choice of "realistic" tests generally results in complex geometries which complicate modeling, thus also complicating the extension of the results from one configuration to another.

This problem had already been mentioned in the former DDBSB seminar[1] on such examples as bullet impact and cookoff. For clarity, the same examples are re-used here and analyzed in more detail in Fig. l, 2 and 3.

1.3   Be informative and meaningful

The upper part of Fig. l illustrates the problem of understanding the outcome of a fuel fire test on an intregrated warhead (i.e. with a built-in fuzing system F). If the warhead detonates after a certain time tin the fire, there is one undisputable conclusion: this munition does not meet a "no-detonation" requirement. However, the next obvious question for the munition developer is "What should I do to correct this situation?". But how can anybody answer this question with just a pass-or-fail test outcome, without adequate instrumentation to understand what happened? In this particular example:

> - did the detonation start in the high explosive HE, exposed to a very high temperature because in contact with the flame through a thermally conductive metal case, or did it start in the fuzing system F, better thermally protected but more sensitive?

> - in any case, what was the temperature when the reaction started?

The impossibility of answering these questions means that a costly test has been done for nothing; therefore it may be worth increasing its cost slightly if this makes it usable. One way of reaching this result is:

> - organizing the test so as to provide more information, in particular by measuring temperatures where they really matter (i.e. in the energetic material) and not just where

they are of easy access (i.e. in the flame, as is usually done);

- breaking down the all-up warhead into homogeneous elements and testing these elements separately, although in a coordinated manner.

This result can be achieved by a two-step test, as follows:

- in the first step, the warhead is tested with its normal HE, but after replacing its fuzing system F with a case of identical thermal characteristics equipped with temperature gauges so as to obtain a temperature history T(t) during the fuel fire;

- in the second step, the fuzing system alone is submitted to that temperature history in a separate oven.

Comparing the times to reaction t_1 and t_2 (or the absence of a reaction) in each step makes it possible to determine which is the weak element in the system. In addition, knowing at what temperatures these events occurred makes it possible to study remedial actions, either by thermal shielding or by modification of the energetic materials.

Incidentally, when a fuel fire test has been set up to last 20 minutes, what valuable information can it provide if the munition reacts after 2 minutes? If the munition detonates it may blow out the flame; but if it reacts only mildly and partially, how is it possible to know what was left of it immediately after the reaction if it is only recovered after 18 more minutes of exposure to fire?

1.4   Be reproducible/reliable

The left-hand part of Fig. 2 illustrates another problem: the reliability of the results of a bullet impact test. This test is done using a specified type of bullet at a specified velocity v, aiming at a given point of the munition so as to hit it exactly along a diameter (without off-centering) in a given cross-section plane. In addition, it is generally assumed that the bullet exhibits no yaw/pitch at impact, so the configuration is fairly symmetrical. But how can anyone be sure of all these assumptions with just a poor visualization of the impact by means of a medium-speed camera at a long distance? This question is particularly important because, if any of these assumptions is wrong, the configuration is no longer symmetrical and the bullet is likely to tumble in a random manner within the munition. Small variations of the test configuration can then lead to considerable differences between two extreme situations:

- if the bullet tumbles, it strongly damages the energetic material (thus producing much surface area) and it may remain within this material as a very hot slug (thus igniting it); given the surface area, this combustion will then be very violent, all the more so as the combustion products can only escape through the one entrance hole of the bullet;

- conversely, if the bullet remains stable, it may perforate the munition from side to side, thus opening two holes in the case instead of one, producing less physical damage than

above in the energetic material and depositing less thermal energy: this energy may be insufficient to ignite the material, and even if it does, combustion will occur in a material with less surface area and with two vents for the evacuation of the combustion products.

Given this considerable influence of random variations, what level of confidence can be placed in the test result?

1.5   Be transferable

Another paper presented at this seminar[2] shows that the level of confidence of pass/fail tests is very poor in general because they are very little informative, and still poorer in the case of bullet impact because they are unreliable: these conclusions require special attention because they are a matter of concern.

Yet, even if this level of confidence were equal to l, the problem of transferability would remain: if the munition does not react to the bullet in the impact test above, this just means that it does not react to that particular bullet hitting it in that particular geometry with that particular velocity, i.e. in a configuration having a zero probability of occurrence in the absence of specified tolerances. There is an infinite number of possible variations of the relevant parameters between the configuration of the test and those of real scenarios: not only random variations as described above, also deterministic variations such as the nature and velocity of the bullet, or its impact trajectories (a few possible trajectories are represented on Fig. 2, but they all are located in meridian planes and normal to the munition axis, while skew impacts are just as likely in real scenarios, and never studied experimentally). So, what allows testers to derive a general conclusion such as "this type of munition is bullet-proof", i.e. to extend the result from that particular test to all real scenarios?

A possible approach to a more general answer is to select a test configuration corresponding to a "worst case" scenario, but there are many possible definitions of such scenarios:

- one possible way of "worsening" the threat is to increase the caliber and velocity of the bullet up to the threshold where its impact generates a prompt detonation;

- however, unless this threshold is reached, the easiest way to "worsen" the threat is just the contrary, i.e. decreasing the bullet velocity, because the probability for this bullet to tumble and to remain within the munition is all the higher as its velocity is lower;

- anyhow, whatever the velocity of the bullet, there is always a "worse-worst case" scenario: this is hitting the fuze.

Therefore, one of the drawbacks of the current approach to purely empirical safety testing is to give a dangerous impression of universality of the responses - e.g. the temptation of declaring "this munition is bullet-proof" after two successful tests done in one particular configuration - while the response to a threat depends on the exact configuration of the real

stimulus. So the only way of assessing safety is to extend results from one configuration to another, and the only universal way to this end is using a mathematical model, as technology now permits and as is already usual - for obvious reasons - in the case of nuclear munitions.

1.6   Case of sequential events.

All the examples considered so far refer to "single" events. In the case of "compound" events (e.g. multiple bullet impact instead of single impact), it is still more difficult to understand the outcome of purely empirical tests, and it is very unlikely that this outcome may be extended to other than the nominal test configuration, given the number of additional parameters likely to influence it. Fig. 3 considers two such parameters in a double impact:

- the time Δt between the two impacts;
- the distance Δz between the two impact points.

If the first impact does not generate a chemical reaction, it has at least a mechanical effect: it produces a cavitation zone in its wake, surrounded by a zone of rubble, then by a fractured zone. It has been shown that mechanically damaged energetic materials were much more sensitive to impacts than the same materials if undamaged[3], so if the second impact takes place within the rubble or the fractured zone, it may initiate a reaction which had not occurred with the first impact. The nature and violence of the reaction then depend on the zone impacted, hence on the distance Δz; and since the boundaries of the damaged zones and the resulting surface area are functions of time, the outcome of the second impact may also depend on Δt , although to a smaller extent.

This, again, raises two different problems:

- the reproducibility of the test per se: Δt is of easy experimental access, but what about Δz? Who can tell for sure where the second bullet hit the munition if this was destroyed by the reaction?

- the possibility of extending the results to other scenarios: even assuming both Δt and Δz to be perfectly known in the test, and all other factors remaining constant, how can it be stated that the result would remain the same for any double impact, i.e. with different values of these parameters?

As in the example of the fuel fire in Fig. l, understanding what happens in a compound event implies to break it down into a sequence of single events, e.g.:

- recover and characterize of the energetic material as damaged by the first impact (even if this is done after a time Δt which is virtually infinite);

- make a single impact in this material with different degrees of damage, as found at various distances Δz from the first impact.

The number of relevant parameters in this sequence of events makes it all the more necessary to utilize models.

2.   Use of Mathematical Models

2.1   Basic approach

Mathematical modeling has been used in safety testing for many years in other fields than munitions. When engineers built a bridge and wanted it to resist a certain load, they did not use full scale testing as a development tool: as soon as materials resistence became a science, the normal way of ensuring safety was (as shown in the upper half of Fig. 4):

> - to achieve a mathematical model of the bridge, incorporating such parameters as elastic moduli or ultimate strengths of the materials to be used;

> - to derive the values of these parameters from simple stress-strain experiments;

> - to validate the model with other experiments, closer to the final geometry but still simple enough to allow easy calculations;

> - to use this validated model to design the bridge;

> - to limit the full-scale tests on the bridge itself to a verification of the calculations (e.g. by measuring its response to concentrated loads within its elastic limits).

2.2   Transfer to munition safety testing

In munition testing, mathematical models are more recent and still not perfect (e.g. bullet penetration is generally simulated in purely axi-symmetrical 2-D configurations which do not take into account the possibility of tumbling), sometimes because of a lack of understanding of some phenomena (e.g. the violence of reaction to slow cookoff). This proves that we are still far from a status where all problems could be solved without any experiment, thanks to ab-initio mathematical codes. But a number of semi-empirical codes are already available, which can be used as tools enabling the transfer of experimental results from the one configuration to another. This approach then leads to an important difference with the current one:

> - in the current approach, tests are supposed to provide a direct and general response by "yes" or "no" to the question "Is this munition safe with respect to this threat/hazard?";

> - in the semi-mathematical approach as described, tests are designed to provide experimental inputs to the model and to validate it; once this is done, it is up to the model to answer the yes-or-no question in each particular configuration.

To this end, tests must be designed in a slightly different way because this approach modifies the order of priority between the four criteria previously described:

- the highest priorities for the test are to be REPRODUCIBLE/RELIABLE in order to ensure the validity of the experimental inputs, and INFORMATIVE/MEANINGFUL in order to allow the validation of the model;

- by contrast, there is no need for the test to be TRANSFERABLE by itself, since the extension of its results from one configuration to another is achieved by the mathematical model with much more reliability than by any purely experimental method;

- as a consequence, the test does not even need to be strictly REPRESENTATIVE of the threat/hazard, since this threat/hazard is just one among the many configurations which can be simulated by the model.

2.3 Illustration on bullet impact

The lower half of Fig. 4 provides a typical illustration of the method:

- when simulating a bullet impact threat, replace the bullet with a sphere, which is less representative but whose penetration is more reproducible (no tumbling or other random behavior) and perform the tests with sufficient visualizations and instrumentation so that the values of all relevant parameters are adequately measured;

- build a mathematical model able to compute the impact and penetration of a projectile of any size and shape (in particular spherical or pointed);

- derive the values of the main parameters of the model from tests done in very simple geometries (e.g. plane targets), then validate the model by means of tests done in more elaborated geometries (e.g. generic munitions, which are more representative but simple enough to give meaningful results);

- use the model to simulate the behavior of a real munition, not only in the particular configuration of the test but in any other as necessary;

- possibly use the model to define the most adequate configurations for final reception testing on the munition itself, if this is estimated necessary (e.g. "worst-case" scenarios having reasonable probabilities of occurrence).

2.4 Illustration on cookoff

Another illustration concerns the cookoff test. For the sake of representativity, a fuel fire is generally simulated with a fuel fire, with all the drawbacks presented above, not to mention environmental considerations. By comparison, a gas fire is cleaner and its outcome can be

much more informative:

      - because the fire can stopped immediately after the event;

      - and because its flame is transparent.

Now, precisely because its flame is transparent, a gas fire differs from a fuel fire: gas flame heating is mainly convective while fuel flame heating is mainly radiative[4]. However this ceases to be a problem if a mathematical model is used. Indeed, as already mentioned, what is important in the understanding of the event is not the temperature somewhere in the flame but the temperature of the energetic material at the time of reaction. This temperature is very difficult to measure directly, but it can be accurately computed out of indirect experimental inputs provided these are of good quality and their boundary conditions well defined, which is certainly easier to obtain with a gas fire than with a fuel fire.

      Since fuel fires might be banned in the near future for environmental reasons, it would be advisable to start preparing an alternative solution now rather than have to improvise one later: this is the rationale already adopted many years ago in the case of nuclear munitions.

2.5   Applicability of the method

All this defines a semi-mathematical approach to the problem of safety testing. Most of its elements already exist, in particular mathematical models (even if they still require some improvements), but the overall approach is not yet usual. However, it is partly implicit in such rationales as the French approach to safety analysis. In this approach, the safety of a munition is not necessarily assessed by means of direct testing: it must be "demonstrated" by any means, including the utilization of results from other tests done in previous phases of the development (on all-up munitions or components, on mockups or even on bare energetic materials). Since the key problem in this approach is the transferability of results from other tests, this requires a combination of experimental testing and mathematical modeling.

3.   Criteria for the definition of test programs

Assuming each individual test to be defined, designed and conducted as previously indicated (in relation with the corresponding threat), it is then necessary to define a coherent test program.

3.l   In early development chases

In the early phases of the development of a munition or family of munitions, and still more if the aim of the tests is to seek improvements to current technologies applicable to all future munitions, standardized specifications are not yet mandatory, so test programs can be defined pragmatically. Actually, they must be defined in an iterative mode because the outcome of each test may lead to modifying its design and because the experience gained from each test

may lead to taking new elements into account. In addition, it is advisable to apply these tests to generic munitions rather than to real munitions because:

- generic munitions normally have simpler geometries, hence they are easier to model and to instrument;

- they are instrinsically cheaper than real ones;

- using them allows the tests (hence the resulting modifications of the design, if any) to be carried out earlier in the process, thus reducing the overall development cost, especially if some of their results can be transfered to the final munition by mathematical means.

3.2   In the qualification chase

In the final phase of a development, this pragmatism is no longer possible because the qualification of a munition is subordinated to mandatory test programs. However, there are several possible approaches to such test programs, whose implications are not only technical but also political[5]:

- the "single label" approach, where the acquisition of a given label (e.g. the IM label in the US Navy MIL-STD 2105, e.g. the EIDS label in the UN "Orange Book") is subordinated to the execution of all the tests appearing in a standard list and to the respect of the pre-defined levels of reaction;

- the "multiple label" approach, where all the tests remain mandatory but their outcome results in a categorization within a graded list of levels (e.g. UN hazard divisions, e.g. the French approach to MURAT specifications);

- the "tailored" approach, where the test program itself is tailored to specific needs, either by eliminating some tests and/or by adapting them case by case, and/or by arranging them in such an order that the outcome of each test allow to take a decision as to the relevance of the remaining ones.

3.3   Approach to "tailored" programs

The revised version MIL-STD 2105B paves the way for the adoption of tailored programs, and so does the draft NATO STANAG 4439 on Insensitive Munitions. Defining such a "tailored" test program applicable to a particular munition or family of munitions requires additional inputs, in particular from operations research, as for the tests by themselves.

- the identification of all likely threats, both environmental (i.e. accidents which may occur during transportation and storage) and combat-generated (e.g. projectile impacts);

- the evaluation of their probability of occurrence in different configurations (e.g. type and velocity of projectile and impact geometry);

- a hazard assessment, i.e. the evaluation of the consequences if one of these threats results in a reaction of a given type;

- the definition of those, among the likely threats above, which deserve sufficient statistical interest to be applied specific tests (the "interest" criterion being, for example, the probability of occurrence multiplied by the severity of the resulting reaction, if any), without excluding further re-definitions as feedbacks from the first results.
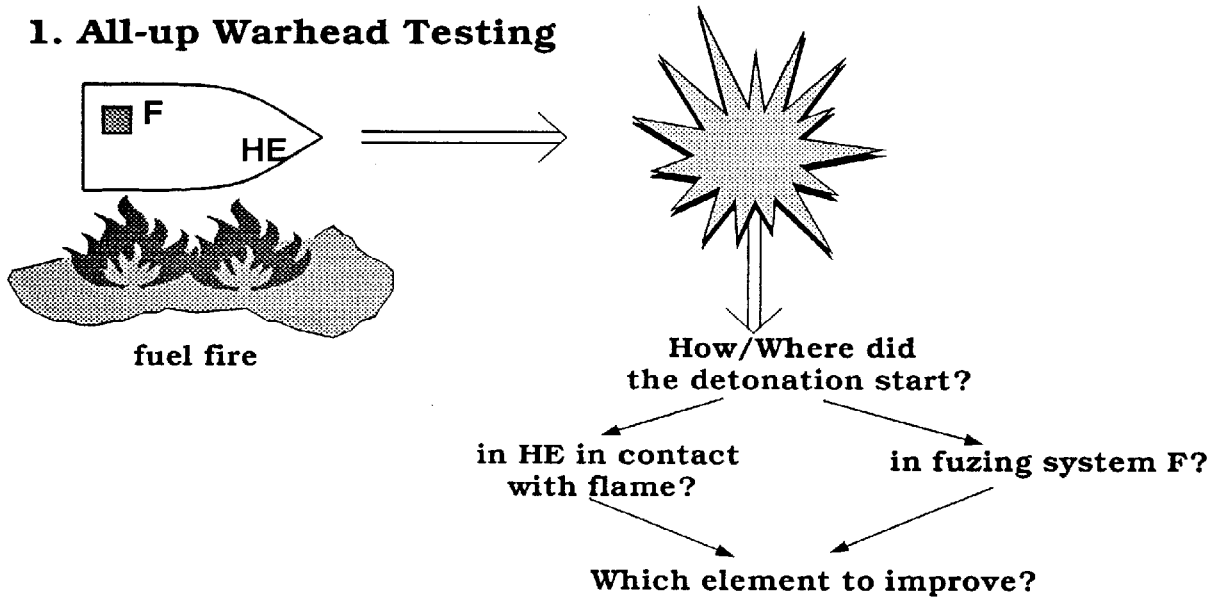
This approach is covered by a separate presentation in this seminar[6], which puts emphasis on a particular category of munitions.

References

(l) M. DéFourneaux and P. Kernen - "Think Before Testing!" - DDESB Seminar, August 1992.

(2) C. Bodart and P. Kernen - "A Statistical Analysis of Safety Test Results and Implications for Insensitive Munitions" - DDESB Seminar, August 1994.

(3) M.DéFourneaux and P. Kernen - "Proceedings of the 1993 NIMIC. Workshop on Sensitivity of Energetic Materials when Fractured or Granular" - Report NIMIC.-S-78-94 (NIMIC.-Limited Distribution).

(4) J.deW. Fitzgerald-Smith, P. Kernen, B.B. Stokes - "Proceedings of the 1993 NIMIC. Worshop on Cookoff" - Report NIMIC.-S-395-93 (NIMIC.-Limited Distribution).

(5) M.DéFourneaux - "Overview of National Policies and International cooperations in the Field of Insensitive Munitions" - ADPA Insensitive Munitions Technology Symposium, June 1994.

(6) J.deW. Fitzgerald-Smith - "A Methodology for Evaluating Potential Threat Hazards to Military Munitions" - DDESB Seminar, August 1994.

Fig. 1 -   Understanding of
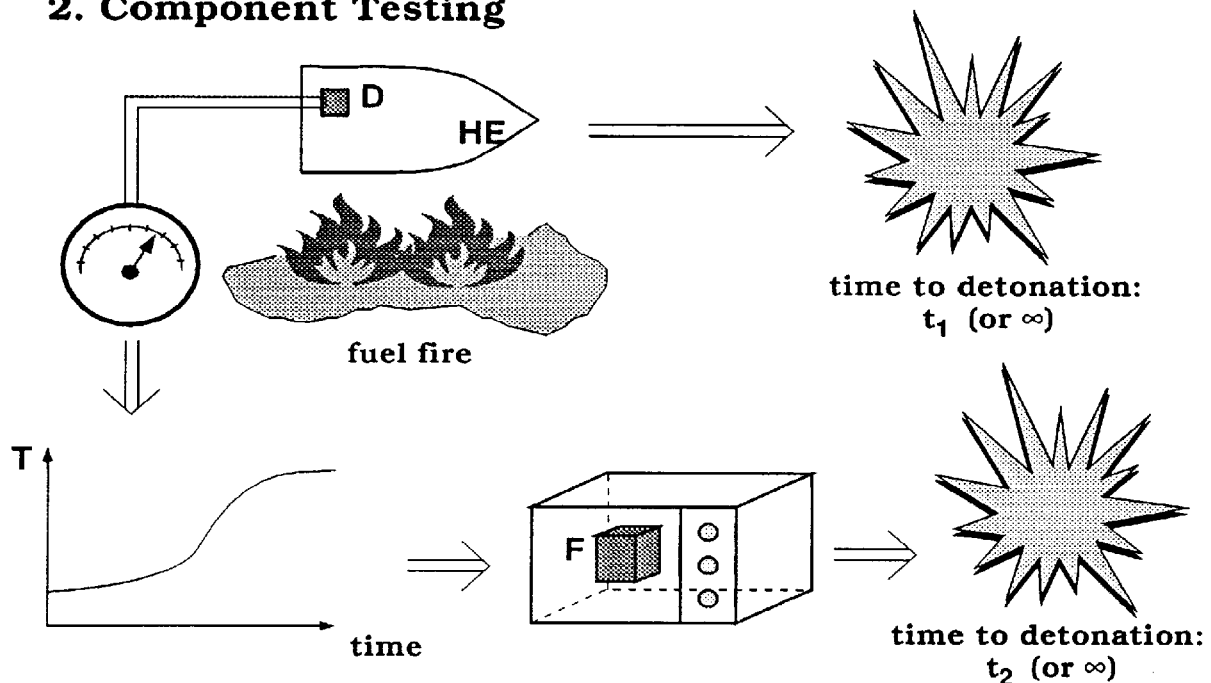## Fuel-Fire Test Outcome

1. All-up Warhead Testing

fuel fire

How/Where did
the detonation start?

in HE in contact
with flame?

in fuzing system F?

Which element to improve?

2. Component Testing

fuel fire

time to detonation:
t_1 (or ∞)

T

time

time to detonation:
t_2 (or ∞)

Fig. 1
Understanding of Fuel-Fire Test Outcome

Fig. 2 - Reliability and Extension of Bullet Impact Tests

Test

Real scenarios

(D)

(E)

(B)

i

(C)

Assumptions for test

- impact in given
  cross-section plan
- no off centering
- no yaw/pitch
- velocity = v ± 0

Real situations

(A) • impact in any plan
  (cross-section or not)
(B) • incidence i ≠ 0
(C) • yaw/pitch y ≠ 0
(D) • other velocity v′
  • other bullet
(E) • combinations of all
  elements above

**HOW CAN YOU BE SURE
OF THESE ASSUMPTIONS?**

**HOW CAN YOU EXTEND
CONCLUSIONS FROM TEST?**
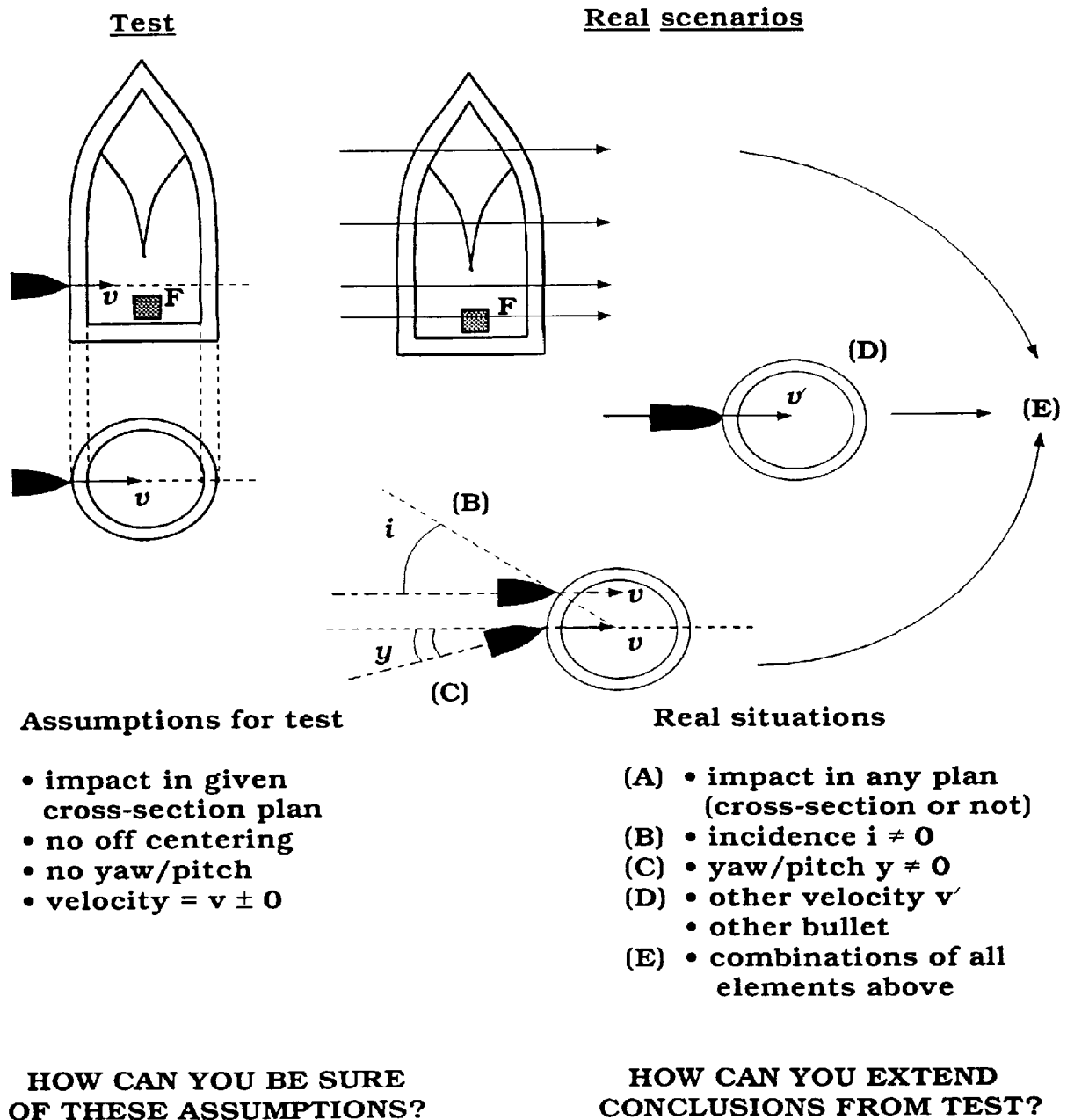
Fig 2
Reliability and Extensionof Bullet Impact Tests

Fig 3 - Double Bullet Impact

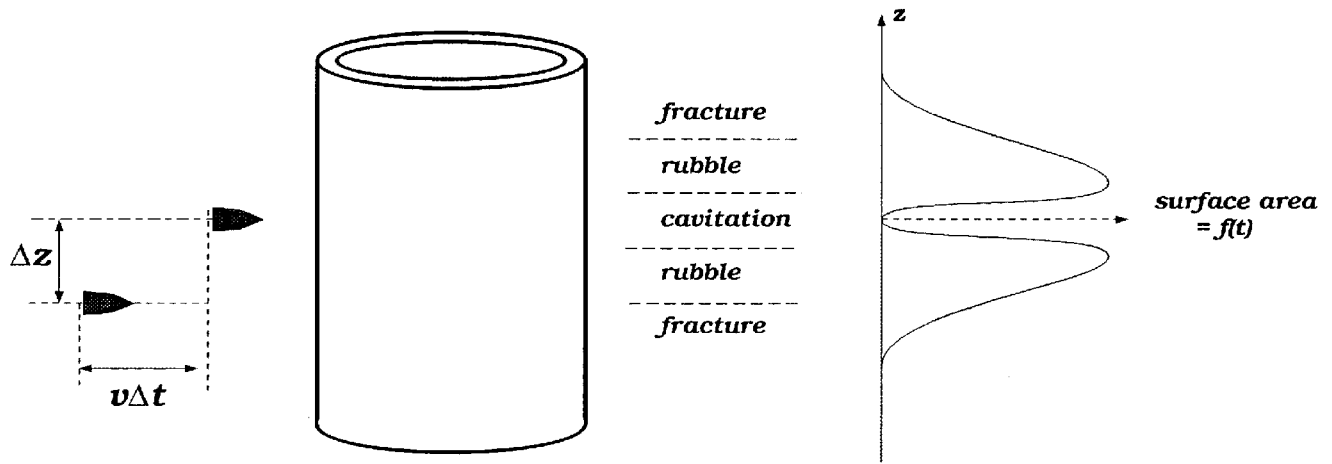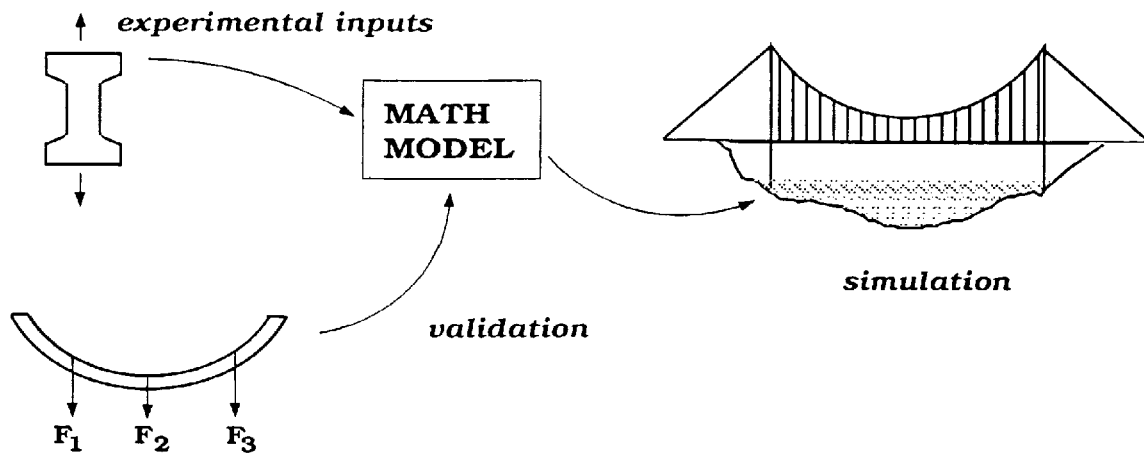**Fig 3**
Double Bullet Impact

Fig. 4 - Coupling Experimental Testing With Mathematical Modeling

1. Civil Engineering

experimental inputs

MATH MODEL

simulation

validation

F₁ F₂ F₃

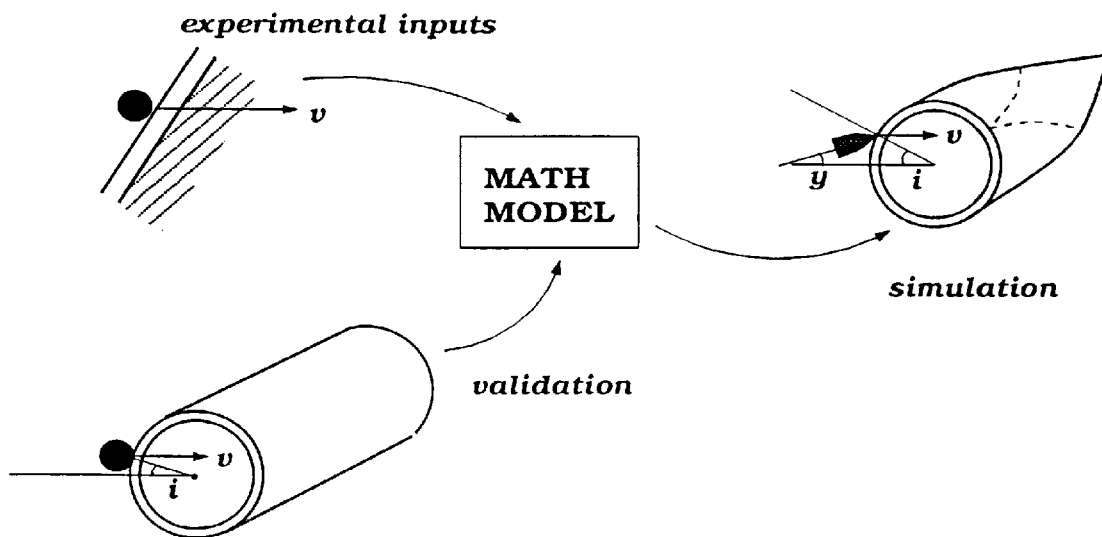## 2. Munitions

experimental inputs

MATH MODEL

simulation

validation

Fig. 4
Coupling Experimental TestingWith Mathematical Modeling